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Experimental and clinical assessment of the accuracy of knee extension measurement techniques

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Abstract The purpose of this study was to analyze the accuracy of commonly used techniques for the measurement of knee extension and to compare them with a new measurement device. The bars of an external fixator were used to determine reference knee extension angles of 15 human cadavers. These angles were compared with measurements of knee extension on radiographs limited to the knee joint. Extension was determined in various knee positions using a generic goniometer and a novel long arm goniometer. In a clinical study, two independent examiners categorized knee extension performance according to the IKDC. Sixteen knees with deficits in the range of motion were rated using a generic goniometer, a long arm goniometer and the novel extension measurement device. The radiological measurement of knee extension angles that were restricted to the shaft of femur and tibia had a systematic error of –5.2±1.9° compared with the lines created by the centers of rotation. In the experimental setup, the mean absolute deviations were 3.92±1.41° with a generic goniometer and 1.22±0.20° with the extension measurement device. The variance of the measurements was significantly lower (2.64±0.28) than with the generic goniometer (23.72±4.39; $P<0.05$). Correspondence in the IKDC rating was 63% using a standard goniometer, 50% with the long arm goniometer, and 96% using the novel device. Radiological measurements of knee extension limited to the area of the knee joint deviates systematically from measurements of the total axis of the bones. A precision goniometer that utilizes bony landmarks of the tibia and femur is superior in accuracy compared with standard and long arm goniometer techniques.

Keywords Knee · Extension · ROM · Goniometer

Introduction

The measurement of knee extension is a key element in the clinical assessment of knee performance. Extension deficits are found in a variety of pathologic conditions. Among those are primary causes such as neurological disorders [14, 35], arthritis [22] or fractures [13, 30]. After knee surgery, extension deficits have been reported, especially after arthroplasties [23, 25], osteosynthesis [30] and reconstruction of the knee ligaments [19, 21, 26]. Therefore, numerous authors point out the necessity of postoperative control of knee extension [15, 28, 32]. After ACL reconstruction, equal side-to-side extension is stressed [32]. An extension deficit of more than 2° in side-to-side comparison leads to a dropdown in overall rating from category A into B according to the International Knee Documentation Committee (IKDC) rating scale [16, 17]. In order to detect such small differences of knee extension, an accurate measurement technique must be used.

Methods for both clinical and radiological knee extension measurements have been introduced, however an analysis of the accuracy of these techniques has not been performed in most cases.

The most common device that is used to clinically assess knee extension is a standard goniometer [10, 20]. It consists of two transparent shafts connected with a joint that displays extension in steps of 2°. The shaft of the standard models has a length of 125 mm. Up to the present point, body landmarks have not influenced the design of the goniometers. Some investigators have used landmarks of the skin for extension measurements [27].

Long arm goniometers have been used in the assessment of hip joint motion [9]. A report of the efficacy of such a device for the knee joint is missing.

Flexometers have been used to determine the range of motion and have been reported as reliable and accurate [4, 9]. However, a comparison with measurements according to the axis of the bones has not been made.

Full passive extension of the knee has been determined radiologically by Howell and Barad [15]. This group used X-rays of the knee that displayed the proximal and distal shaft of tibia and femur. The posterior cortices of tibia and femur were used as reference lines that enclosed the knee extension angle. A comparison of this extension angle with the one that is enclosed by the entire shaft of both tibia and femur was missing.

In experimental studies two approaches have been used to measure knee extension angles: External goniometers that were fixed to the lower extremity have been used in a series of trials [1, 2, 3]. Townsend developed a electromechanical goniometer in order to describe gait abnormalities [34]. He already mentioned the importance of linkage of the bars to bony references of femur and tibia. The bars of the device were attached to the skin using elastic ECG bands. However, the accuracy of the device was never tested and a comparison with X-rays has never been published.

In cadaver studies most authors have used cemented stems as a longitudinal extension of the shafts of tibia and femur [6, 12, 18, 24]. Both bars were then attached to an extension measurement device such as a robotic system. Up to the present point, this procedure has not been compared with the radiological or clinical measurement techniques.

The purpose of this study was to investigate the accuracy of clinical and radiological measurements of knee extension angles. A knee extension measurement device that uses bony landmarks on tibia and femur was developed. It was tested in a cadaver study, in order to evaluate its accuracy in comparison with a measurement device attached directly to the bones and to exclude a systematic measurement error. Radiographic measurements of knee extension were also investigated. In a second step, a prototype of the novel device was compared with a standard and a long arm goniometer. The interobserver accuracy of the determination of the ROM using a common rating scale was analyzed.

Materials and methods

The knees of 15 human cadavers were examined in the Department of Forensic Medicine of the Ludwig-Maximilian-University in Munich for this study. The age was 46.0±10.5 (range 31–67) years. The time between decease and examination was 2.7±1.2 (range 1–4) days. We used the legs of 14 men and one woman; the group had a height of 177.6±7.6 (range 163–191) cm and a weight of 80.9±14.5 (range 60–103) kg. The knee and hip joints were passively moved through the full range of motion 20 times to reduce tissue stiffness caused by rigor mortis. An external fixator was applied to the proximal and distal anterior shaft of the tibia and femur (Fig. 1). The knee was flexed 90° and sagittal X-rays of the entire tibia and femur were taken. Images that were poor in contrast or did have an overlap of the femoral condyles of more than 5 mm were repeated. If the entire femur did not fit on a single X-ray, another overlapping image was taken.

The centers of rotation of femur and tibia were constructed as follows:

1. Center of the femoral head.
2. A point 20 mm above the joint line (i. e. a corrected 22 mm on X-rays) of the knee located at two-thirds of the diameter of the femoral condyles. This point has been described as the compromise axis for the line composed by the centers of rotation. It shows the least deviation if a hinged joint is superimposed on the sagittal knee [7, 29].
3. Midpoint of the tibial plateau.
4. Center of the sagittal ankle joint.

The external fixation bars were aligned parallel to the constructed axis of rotation (Fig. 1).

The angles between the axis of rotation and the lines that were drawn parallel to the posterior cortex of the tibia and femur within the proximal and distal 150 mm of the joint line were determined.

A long arm goniometer was attached to the bars of the external fixator in order to display extension angles by analogy with the radiological determined extension axis (Fig. 2).

A long-arm electrogoniometer was equipped with a mould that rests on the proximal shaft of the anterior tibia. It is angled at +3.4° in relation to the lower arm of the goniometer in order to adjust for the angles created by the anterior cortical line of the tibia in relation to the bone axis of the tibia and the angle created by the antetorsion of the femoral head in relation to the greater trochanter. These angles were analyzed using the sagittal radiographs of 15 entire tibias and femurs. The femoral end was connected to an adjustable, anatomically shaped cup that fits to the greater trochanter of the hip. In the center of rotation a digital incremental signal transducer was attached. One signal was received every 0.34° (Fig. 2).

The knees were positioned in different knee extension positions (maximal hyperextension with a force of 500 N directed anterior-posterior to the patella, full passive hyperextension, extension with the lower extremity laying flat on the examination table, 15°, 30°, 60°, 90°, 120° and maximal flexion) in a random order. Extension of 15°, 30°, 60°, 90°, and 120° was approximated to ±10° to make the observer unconscious of the true extension angle. The true extension angles were recorded using the long arm goniometer that was attached to the external fixator. The bars were covered with a drape in order to avoid any bias of measurements (Fig. 2).

An independent observer determined knee extension with a standard goniometer as described in other studies [10, 31] using the greater tuberosity, the middle of the knee joint, and the distal end of the fibula as landmarks. The novel goniometer was then put on the lower extremity. After calibration of the device at 0°, the extension angle was recorded.

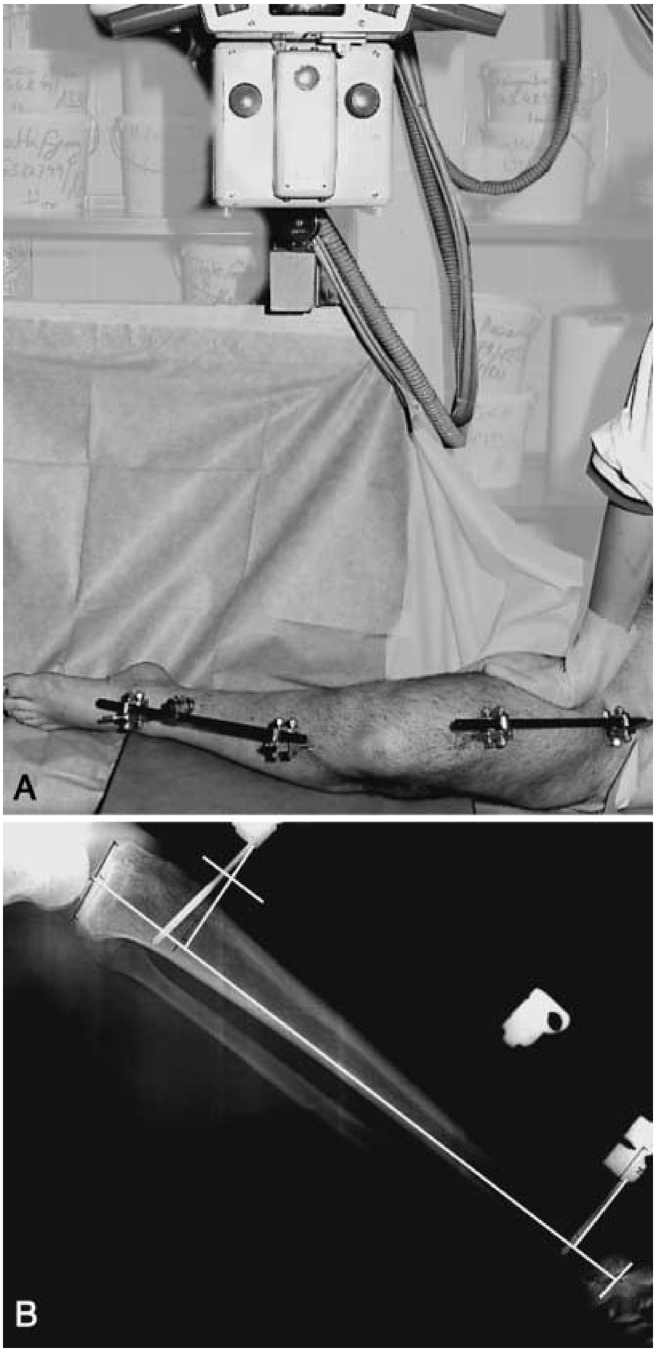

Fig. 1A, B After an external fixation device was applied, radiographs of the entire femur and tibia were taken at 90° of knee flexion. Lines were drawn from the middle of the ankle joint to the middle of the tibial plateau. Another line indicated the posterior cortex of the tibia within 15 cm of the joint line. The bar of the external fixator was brought into a parallel position with the constructed axis of the tibia. The procedure was performed by analogy for the femoral lines and fixation bars

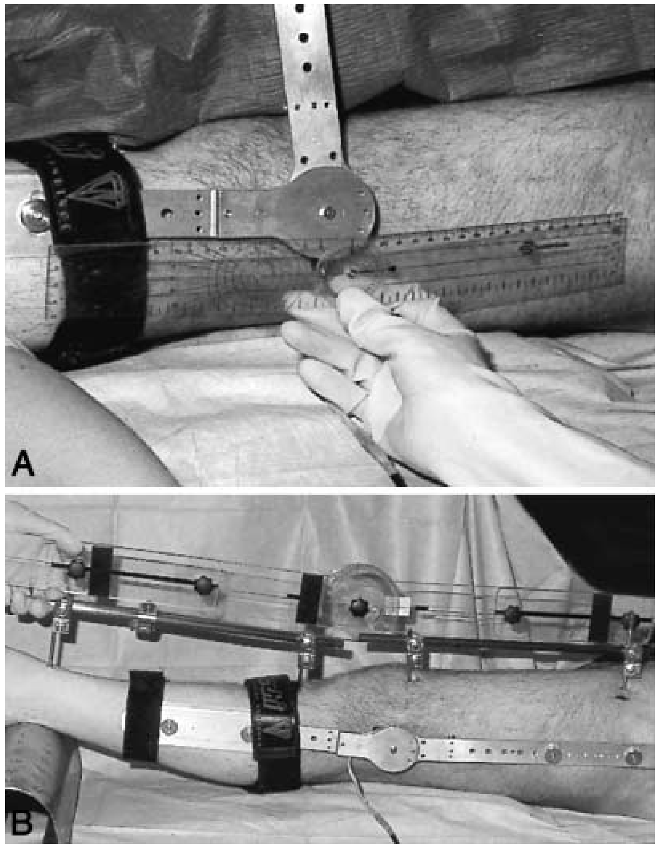

Fig. 2 **A** Goniometric measurements of knee extension. The bars of the external fixation device were covered to avoid bias. An independent observer determined knee extension using the joint line, the distal fibula and the greater trochanter as reference points. **B** The novel extension measurement device was posted against the anterior tibia and the greater trochanter using anatomic moulds. Aligning the rods of the external fixation device parallel to the axis of rotation of hip, knee and ankle under radiographic control, the reference knee extension angles were determined using a long arm goniometer

Clinical investigation

Sixteen knees with various degrees of extension and flexion deficits (median 5.1±4.3° extension deficit and 23.3±20.4° of flexion deficit were examined in a rehabilitation center (Eden-Reha, Donaustauf, Germany). Twelve men and four women were recruited for the study, the mean age was 37.8±8.6 years. The pathologic side was in seven cases the left and in eight the right knee. The examination was performed with a standard goniometer, a long arm goniometer and an analogue prototype of the novel goniometer that was used in the first part of the investigation. The results were used to rate the knees according to the IKDC [16, 17]. The procedure was performed by two independent examiners who were instructed to use a standard measurement technique. The participants were asked to passively flex their knees as far as tolerated in a supine position on the examination table, using their hands to assist flexion if possible. This position was kept for the time of all measurements. Since the goniometer was the less accurate measurement technique in the experimental part of the study, these measurements were performed first by analogy. Secondly, the participants were examined with the long arm goniometer and the novel appa-

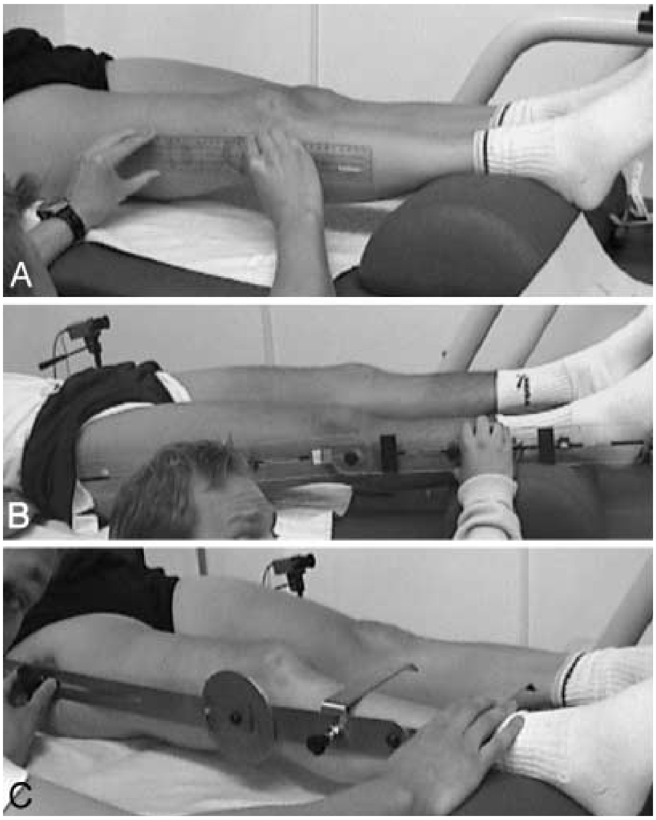

Fig. 3A–C Clinical determination of knee extension using a standard goniometer technique (**A**), the long arm goniometer with adhesive marks of anatomical landmarks (**B**) and the novel goniometer with moulds of the anterior tibia and greater trochanter (**C**)

ratus in a randomized order. For the measurements with the long arm goniometer, the examiners marked the distal head of the fibula, the middle of the knee joint at the level of the joint line and the greater trochanter of the femur using adhesive markers. All marks were removed before the second examiner repeated the measurement. The second observer repeated the measurements immediately after either instrument was used by the first investigator to avoid any changes in knee extension. After flexion measurements, the heels of the patients were put on a cushion. The patients were asked to relax their legs with their knees elevated above the surface of the examination table. This position was kept for 5 min before the measurements were repeated by analogy with the procedure for the flexed position (Fig. 3).

Statistical analysis

Discrepancies between the radiological measurements of the radiographs were analyzed using the mean, standard deviation and range. The measurement errors of the goniometric and extension device measurements were calculated as absolute values, means± 1 SD, and range. We performed a transformation of the measurement error values into normalized *Z*-values; We concluded that there was no systematic bias if normalized *Z*-values were within ±1.64 (95% confidence interval for a normal population). The variance of the two measurement techniques in the experimental trial such as the interobserver variance of the clinical measurements were examined using *F*-values and a single tailed *F*-test; a significance level of 0.05 was used [5, 11]. All calculations were performed on an IBM compatible computer using Excel for Windows 7.0 (Microsoft) and SigmaPlot 5.0 (SPSS-Company).

Results

Radiological measurements

The angle between the line drawn vertical to the tibial plateau and the line drawn through the middle of the tibial plateau and the middle of the ankle was –3.0±1.1° (range –4 to –1°); the angle between the line parallel to the posterior cortex of the femur and the line drawn through the center of the hip and the compromise axis of the femoral condyles was determined at –2.2±1.3° (range –4–0°). This gave a total difference in knee extension measurement of –5.2±1.9° (range –8 to –2°; Fig. 4).

Knee extension measurements

When the external fixator was used for extension measurement, full forced hyperextension (500 N) of the knees in this study was –7.67±7.04° (range –23.0–3.0°), passive extension –2.1±6.1° (range –16.0–5.0°). In the neutral position (lower extremity flat on the examination table) extension averaged 1.52±4.07° (range –5.0–6.0°). The mean extension angles for the approximation of 15° were 16.27±5.26° (range 5.0–25.0°), of 30°, 32.8±7.49° (range 25.0–48.5°), of 60°, 58.08±11.23° (range 36.0–76.0°) of 90°, 93.57±7.79° (range 80.0–106.0°), and of 120°, 124.40±10.11° (range 110.0–142.0°). Full flexion of the knee resulted in a mean 142.20±10.85° (range 128.0–164.0°) angle.

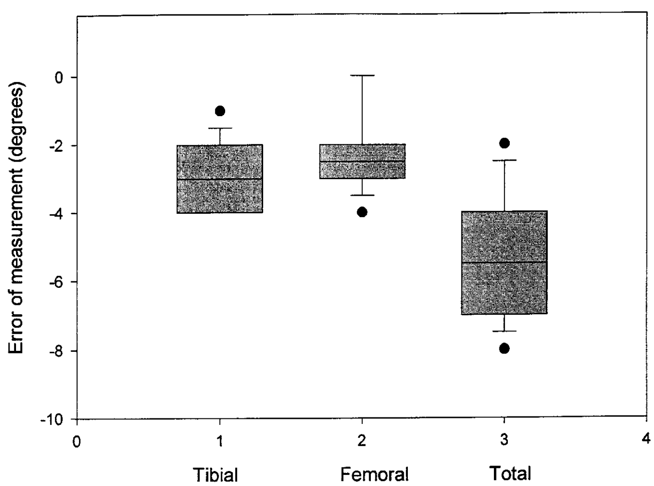

Fig. 4 Error in measurement of knee extension using radiographs limited to the proximal and distal 15 cm of the joint line as compared to measurements using the axis of the entire femur and tibia

Table 1 Standardized *Z*-values for the discrepancies between the mean true extension angle and the angle obtained using one of the two measurement techniques. All values were in between the margins for the 95% confidence interval of a normal distribution (±1.64)

	Goniometer	Extension measurement device
Max. extension	–0.83	0.14
Pass. extension	–0.46	0.16
~0°	–1.22	–0.67
~15°	–0.33	–0.46
~30°	0.19	–0.53
~60°	0.14	–0.37
~90°	–0.71	–0.12
~120°	0.69	0.17
Max. flex.	1.40	0.06

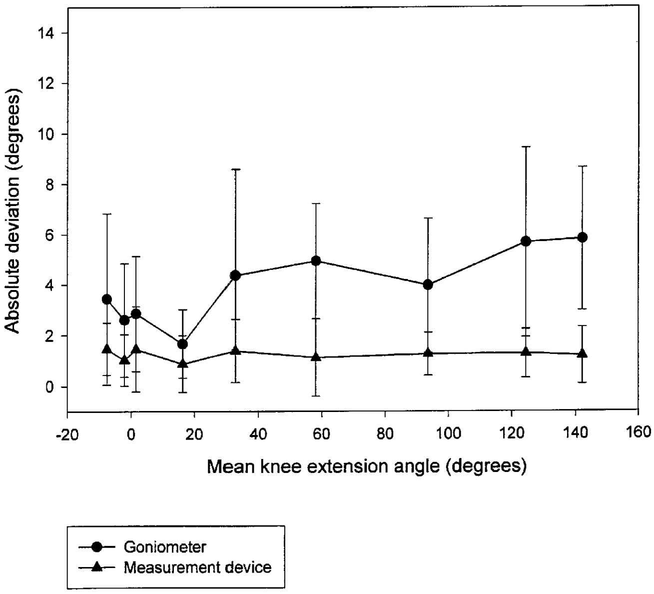

Fig. 5 Absolute values for error of measurement between goniometric determination of knee extension and an extension measurement device that is posted against bony landmarks of femur and tibia. The absolute values are shown with the knees positioned in maximal extension, full passive hyperextension, flat on the examination table, ~15°, ~30°, ~60°, ~90°, ~120° and full passive flexion (from left to right). There were significant differences between the variances of the measurement errors of both techniques throughout the observed range of motion (*F*-test, compare)

Analysis of the standardized measurement errors of the two extension measurement techniques revealed that all of the *Z*-values were within the 95% interval enclosed by the ±1.64 margins. Hence no systematic bias of the methods could be detected with the given number of cases (Table 1).

The goniometric determination of knee extension (method A) had an absolute mean error of measurement of 3.92±1.41° (range 1.67–5.80°), the measurements with the extension measurement device (method B) resulted in 1.22±0.20° of error (range 0.87–1.46°; Fig. 5). If a measurement range of 180° is assumed, this means a relative measurement error of 2.2% for method A and of 0.6% for method B. The variance for method A was 23.72±4.39 (range 4.55–45.03) and for method B 2.64±0.28 (range 1.60–4.53). *F*-test indicated that the variance of the extension measurements with method B was significantly lower at all examined knee positions (Table 2). The variance of the goniometric measurements was significantly lower with the knee in the flat on examination table position compared with all other extension positions ($P<0.05$).

Table 2 Error variance and corresponding *F*-values for the comparison of both measurement techniques in the cadaver study: measurements with the extension measurement device were associated with a significantly smaller variance at all knee extension positions

	σ Goniometer	σ Extension measurement device	*F*-value	*F*-test (single tailed)
Max. extension	21.68	3.26	6.66	<0.01
Pass. extension	11.64	2.06	5.65	<0.01
~0°	12.15	4.53	2.684	0.04
~15°	4.55	1.60	2.843	0.03
~30°	38.09	2.45	15.52	<0.01
~60°	31.11	2.39	13.02	<0.01
~90°	21.75	2.33	9.322	<0.01
~120°	45.03	2.44	18.48	<0.01
Max. flex.	27.50	2.72	10.09	<0.01

Clinical results

The measurement devices are reported as GON (Goniometer), LAG (long arm goniometer) and NEW (novel goniometer). Observer one determined knee extension of the injured knees at +6.9±5.8° (range: 25; –1°) using the GON, +3.4±5.9° (17; –10°) with the LAG, and +1.6±5.0° (16; –5°) with the NEW. For the uninjured knees, observer one measured the extension angles as +1.9±5.5° (10; –8°) with the GON, –0.3±4.5° (9; –8°) with the LAG, and –2.6±5.1° (7; –13°) with the NEW. This resulted in a side-to-side difference of 6.3±5.4° (21; 0°) determined by GON, 4.3±5.2° (20; 0°) by LAG, and 5.1±4.3° (16; 0°) by NEW measurements.

Observer one detected knee flexion of the injured knees at 126.0±19.6° (range: 150; 72°) using the GON, 124.0±20.5° (150; 64°) with the LAG, and 124.3±20.2 (150; 67°) with the NEW. For the uninjured knees, observer one measured the flexion angles as 147.2±11.2° (162; 130°) with the GON, 146.6±10.6° (160; 122°) with the LAG, and 147.6±9.3° (160; 128°) with the NEW. This resulted in a side-to-side difference of 21.2±20.5° (78; 0°) determined by GON, 22.6±20.4° (84; 2°) by LAG, and 23.3±20.4° (80; 4°) by NEW measurements.

Table 3 IKDC evaluation of both observers (*O1*, *O2*) using a standard goniometer (*GON*), a long arm goniometer (*LAG*), and the novel precision goniometer (*NEW*) in the clinical trial. Below the interobserver correspondence (*IOC*)

	Extension						Flexion						Overall					
	GON		LAG		NEW		GON		LAG		NEW		GON		LAG		NEW	
Cat.	O1	O2	O1	O2	O1	O2	O1	O2	O1	O2	O1	O2	O1	O2	O1	O2	O1	O2
A	3	6	8	6	5	5	3	3	1	4	1	1	0	1	0	1	0	0
B	4	4	4	5	6	5	6	5	8	4	8	6	4	4	8	5	7	6
C	6	3	3	1	4	6	3	4	3	2	1	3	7	6	4	2	3	4
D	3	3	1	4	1	0	4	4	4	6	6	6	5	4	4	8	6	6
IOC	44%		44%		88%		81%		56%		88%		63%		50%		94%	

Observer two reported knee extension of the injured knees as +4.8+/–4.8° (range: 16; -6°) using the GON, +4.7±5.1° (17; –2°) with the LAG, and +0.9±4.3° (12; –6°) with the NEW. For the uninjured knees, observer two determined the extension angles at +1.7±4.3° (9; –9°) with the GON, –0.3±4.5° (9; –7°) with the LAG, and –2.3±5.7° (8; –13°) with the NEW. The side-to-side difference was 5.3±4.0° (13; 2°) with GON, 5.6±5.4° (19; 0°) by LAG, and 4.9±4.3° (16; 0°) with NEW measurements.

Observer two recorded flexion of the injured knees with 125.6±17.9° (range: 150; 72°) using the GON, 124.3±21.7° (155; 63°) with the LAG, and 124.4±20.0° (152; 66°) with the NEW. For the uninjured knees, observer one measured the flexion angles as 145.6±10.0° (160; 130°) with the GON, 146.9±9.6° (159; 126°) with the LAG, and 147.3±9.5° (161; 126°) with the NEW. This resulted in a side-to-side difference of 20.0±18.9° (77; 0°) determined by GON, 22.7±22.3° (85; 1°) by LAG, and 22.9±19.8° (80; 0°) by NEW measurements.

The corresponding IKDC scores for both observers and the percentages of interobserver correspondence are shown in Table 3.

The absolute discrepancies between both observers for all measurements were 3.3±3.1° (13; 0°) for GON with a variance of 9.6, for LAG 3.3±2.9° (13; 0°) with a variance of 8.3, and for NEW measurements 1.5±1.3° (5; 0°; variance: 1.6). *F*-Test indicated that there was no significant difference between the variances of the GON and LAG measurements (P=0.57); however, the variances of NEW measurements were significantly lower compared with GON and LAG (P<0.01).

Discussion

The determination of knee extension is a widespread tool in the evaluation of posttraumatic or postoperative knee performance [32, 33]. According to the IKDC-Knee score [16], a difference in knee extension of >2° has to be detected in order to categorize knee function properly. This study analyzed different commonly used techniques to determine knee extension. A measurement device that facilitates the measurement of knee extension by putting anatomically shaped moulds against the greater trochanter of the hip and the anterior surface of the tibia was developed and tested both in a cadaver and clinical study.

The examination of the radiographs of knees in full passive hyperextension has been advocated, as two observers have reached high interobserver reliability in the measurement of the extension angle using the posterior cortex of the femur and tibia as reference lines [15]. However, the results of this study indicate that there is a systematic measurement error of approximately –5° compared with the angle that is obtained when the entire axis of femur and tibia are used. In appreciation of this result, the report of an average passive knee extension of –10.2± 5.7° found in the above mentioned series of 33 knees that matched a normal population [15] translates into an average of approximately –5° of hyperextension when the long axis of the bones are used. A similar error affects experimental setups that use only the distal shaft of the femur and the proximal shaft of the tibia [36, 37].

A standard goniometer used in a fashion described in previous studies [8, 10] had a mean measurement error of >3° in the determination of full hyperextension, such as in all observed extension positions of >15° flexion in the experimental part of this study. The most accurate measurements were made close to 0° extension. However, in this position the observer may have been biased as the extremity was lying flat on the table; this may have caused a constant measurement close to zero.

In our clinical trial, both the standard goniometer and a long arm goniometer technique failed to providem sufficient interobserver reliability. The interobserver variance of measurements made with the novel goniometer was significantly lower (P<0.01). However, even with this technique, correspondence of IKDC categories between both observers was only 88% for flexion and extension measurements. These results demonstrate the difficulties that exist in the determination of knee extension. In our experience, small changes in the extension angles may occur during measurements as soft tissue may relax or flexion may decrease as a reaction to pain. We therefore stress the necessity to determine the ROM under the same conditions every time and to set up rules for reliable measurements.

An extension measurement device that uses the support of the greater trochanter and the anterior surface of the tibia significantly improved the accuracy of extension measurements and had an accuracy of <2° throughout the full range of motion in the experimental study. Between two independent observers, the mean discrepancy was only 1.5±1.3° for clinical measurements.

In conclusion, radiological and experimental measurements of knee extension result in a misinterpretation of knee extension of approximately –5° when the measurements are restricted to the proximal and distal shaft of the femur and tibia.

Goniometric measurements of knee extension are sufficient for evaluation of the range of motion when a mean error of measurement of >3.5° can be tolerated.

An extension measurement device as used in this study significantly improves the accuracy of extension measurements of the knee. It may be useful for the evaluation of knee extension both in clinical investigations such as in daily practice for physicians and physiotherapists as a means to document the range of motion and to categorize knees according to the IKDC rating scale.

Due to its unique design with moulds that fit in-between the straps of a knee brace, the instrument can be used to determine the limitation of the range motion that is implemented on the knee by an orthosis. If a functional knee brace is designed to facilitate full passive hyperextension (Hypex, Albrecht, Neubeuern, Germany), the measurement device can be used to control the adjustment of the limitation of hyperextension.

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